CALCULATION OF FRACTURE RISK INDEX TO ASSESS THE RISK OF BONE FRACTURE DURING SPACE EXPLORATION MISSIONS

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A bone fracture risk assessment model has been developed as a module within NASA's Integrated Medical Model to quantify the risk of bone fracture during space exploration missions to the moon and Mars. The model is scenario-based, providing predictions of fracture at any specific time during a mission and predicated on a specific task or event. Input to the model includes mission parameters and crew statistics, such as the gravitational environment, the mission length, whether the activity was internal or external to the vehicle, crew age, weight, height, gender and pre-flight BMD levels.

The model provides an important step in assessing risk by calculating a bone Fracture Risk Index (FRI) which is the ratio of the skeletal loading generated during different activities and the ultimate strength of the astronaut's bone as a function of a time-dependent estimate of BMD. The risk of bone fracture at the proximal femur and the lumbar spine was assessed for routine mission tasks such as lifting and during activities which could result in high impact loading, such as a fall from a ladder. The model focuses on the femoral neck and at the lumbar spine, since these locations exhibit high localization of bone loss and due to the medical severity with fracture at these sites.

Directly measuring the loads on the intact skeletal systems is invasive and not practical. Therefore skeletal loads for each different activity were estimated using a series of biomechanical loading models corresponding to activities and events likely to occur during space exploration missions. Rigid links were used in static loading models to represent the bones of interest and the loads were found through summation of the forces and moments unique to the particular activity. A mass-spring-damper model was used in the dynamic loading models to estimate the loading experienced from a high impact force. There was uncertainty associated with many of the model parameters, including body segment lengths and masses, upper body center of mass, stiffness and damping characteristics of bone, muscles, connective tissue, spinal discs and space suit material, orientation and location of load and ground surface characteristics.

The Ultimate Strength of the bone, i.e., the loading above which fracture will occur, is known to be dependent on bone density, geometry and microarchitecture. For the initial development of the model, the Ultimate Strength is considered to be strictly a function of BMD, based on data availability. A time-dependent estimate of BMD change as a result of spaceflight was obtained from a combination of relevant bone loss data, including existing pre- and post-flight BMD measurements, BMD measurements from ground-based analog bed rest studies and long-term BMD measurements of patients with spinal cord injuries. A review of biomechanical and clinical research provided data with which to build a model of Ultimate Strength as a function of BMD. Numerous studies report the ultimate strength of bone excised from cadavers resulting from testing in material testing systems (MTS). However, such measurements are taken under conditions different than *in vivo*. For example, cadaver bone tested in an MTS is not typically surrounded by body tissues and fluids as they are *in vivo*. In addition, the exact arrangement of force application that causes a fracture *in vivo* is unknown and may be different from the arrangement used during MTS testing. For our model, care was taken to use data from ultimate strength studies that applied force to the bone specimen in a manner which most closely resembled the force application expected during the particular activities of interest. Despite the special attention paid to the orientation, magnitude and loading rate of the applied force, an uncertainty is present within these parameters and in the loss of astronaut BMD as a function of time.

To account for the uncertainty of the model parameters due to variations within the population and unknowns associated with the effects of the space environment, a distribution of values were used to describe the input parameters. The FRI was not calculated as an absolute value, but instead a Monte Carlo simulation was performed to obtain a probability density function for the FRI. Results indicate that there is a small, but non-negligible risk of bone fracture during a Mars mission. The impact of bone fracture to the mission was quantified by examining the level of treatment available during the mission, which will be less than the best care available on Earth. Even the best terrestrial care has a finite probability of chronic disability or death due to a severe fracture. In the restrictive medical care environment of space, a severe fracture could cause loss or impairment of at least one crew member during a mission and have a major impact on the mission. Future work will include designing experiments and conducting reviews which will result in more detailed information about the most sensitive parameters so that the model uncertainty can be reduced.